Chapter 1

Experiment # 1: Wheatstone Bridge

1.1 OBJECTIVE

When you have completed this experiment you will

- know the principle of operation of the basic Whetstone Bridge.
- know how to measure resistances using a Wheatstone Bridge.
- understand the effect on the sensitivity of the bridge of varying the following parameters:
  - resistance of ratio arms.
  - ratios of the arms.
  - source voltage
- understand the operation of the basic operational amplifier.
- know how to connect up an operational amplifier to act as a voltage amplifier.
- understand the terms ‘differential gain’ and ‘common mode gain’.

1.2 BACKGROUND THEORY

1.2.1 Basics of Wheatstone Bridge

A method of determining resistance which is not direct reading has many sources of error. A direct reading method with few error sources would be of great advantage. A way of
determining resistance value which only requires one meter is shown in the circuit of Figure 1.1. Here, the unknown resistance, \( R_x \), is used in a potential divider circuit with a known standard resistor \( R_s \) connected across a known source \( V_s \). From the potential divider formula

\[
R_x = \frac{V}{V_s - V} R_s
\]  

(1.1)

This circuit suffers from some disadvantages. Obviously \( R_s \), the standard resistor, must be known precisely. The voltmeter \( V \) must have a resistance very much greater than \( R_x \) for accurate results (to avoid loading the circuit). This method does not lead to direct reading of the result. When all the circuit values are known precisely, the final accuracy still depends ultimately on the accuracy of the meter indication. It would be advantageous to find a method which does not have these drawbacks.

Consider the circuit of Figure 1.2. Here, there are two voltage sources of \( +V_s \) and \( -V_s \) volts. The resistor \( R_x \) is a variable calibrated standard resistor, \( R_s \) is the unknown resistance, and
$M$ is a center-zero ammeter. The meter reads zero when the voltage at the junction of $R_s$ and $R_x$ is zero. Assuming $R_s$ has a calibrated scale, $R_x$ will be proportional to $R_s$ provided that the two voltage supplies are of the same magnitude but have opposite signs.

Consider the circuit in Figure 1.3. With the switch closed, the needle will be at its zero position. When the switch is open, any current flowing through the meter will cause the needle to move, and it is possible to detect very small movements of the needle. This method then gives a very sensitive indication of the zero position. One disadvantage of the circuit in Figure 1.3 is that $+V_s$ must be equal in magnitude and opposite in polarity of $-V_s$.

By using another voltage divider using two equal resistors $R_1 = R_2$ as shown in Figure 1.4, we can use a single voltage source of $V$ volts such that the meter is connected to a point of potential $V/2$ volts. The resistors $R_1$ and $R_2$ are called the “ratio arms” of the circuit and the circuit as a whole is called a Wheatstone Bridge. It is more often drawn in the form of Figure 1.5.
1.2.2 Sensitivity of Wheatstone Bridge

Let’s first define the term ‘sensitivity’ as related to a Wheatstone Bridge. What we are really after is a large change in meter indication for a small change of the standard resistance, so that the balance point of the bridge may be accurately determined. The sensitivity of a bridge may be defined as the rate of change of meter current with small changes of the standard resistance about the balance setting. For a given meter, with a given sensitivity, let’s try and determine if there are any properties of the bridge itself which affect the sensitivity and accuracy of measurement. The parameters of the bridge circuit that can be varied are:

- Resistance of ratio arms.
- Ratios of the arms.
- Source voltage.

Figure 1.5: Circuit of Wheatstone Bridge.
1.3 PROCEDURE:

1.3.1 Task # 1: The basic Wheatstone Bridge.

- Set up your module as in Figure 1.6.

- An extra 220 Ω resistor is included in the module circuit in series with the Wheatstone Bridge to limit the current in event of a short circuit when connecting and using the Wheatstone Bridge.

- Connect a resistor of about 100 Ω across the $R_x$ terminals.

- On the Wheatstone Bridge, set switches SW1 and SW5 'ON' and all other switches 'OUT'. This will set both $R_1$ and $R_2$ at 100 Ω.

- Slowly increase the variable dc voltage, using the potentiometer on the Operational Amplifier, to give a supply $V_s$ of 10 V. Adjust $R_s$ to achieve zero deflection (i.e. a balanced bridge condition) making use of the meter switch to obtain an accurate balance.

- The recommended technique is to adjust $R_s$ to a value such that there is minimum, ideally no, movement of the meter reading when the switch is switched ON and OFF. The use of this method minimizes any error due to the meter set-zero adjustment.

- Read the value of $R_s$ from the resistance box and record your results in Table 1.1.

- Disconnect the 100 Ω resistor and substitute a 1000 Ω resistor for $R_x$. Repeat the balancing procedure and read the new value of $R_s$.

- Repeat the procedure to complete Table 1.1.

1.3.2 Task # 2: Effect of Resistance Arm Value

- Set up the circuit as shown in Figure 1.7 (Note that the series resistor is not included in the bridge connection for this circuit).

- Set $R_s$ at 1 kΩ.

- On the Wheatstone Bridge, set switches SW1 and SW5 'ON' and all other switches 'OUT'. This will set both $R_1$ and $R_2$ at 100 Ω.
• Ensure that the Operational Amplifier potentiometer knob controlling the dc voltage is at zero, and switch on the power supply.

• Set the variable dc voltage to approximately 10 V.

• Balance the bridge and record the setting of $R_s$ in Table 1.2.

• Increase the setting of $R_s$ by 100 Ω (10%) and record the out-of-balance current flowing through the meter.

• Change $R_1$ and $R_2$ to 1 kΩ and repeat the balancing procedure and determine the 10% out-of-balance current as before. Record the results in Table 1.2

• Complete Table 1.2.

1.3.3 Task # 3: Effect of Resistance Arm ratios

• Set $R_x$ at 1 kΩ.

• Set $R_1$ to 1 kΩ and $R_2$ to 100 Ω. Balance the bridge and record the setting of $R_s$ in Table 1.3.

• Increase $R_s$ by 10 % (10 Ω) and record the out-of-balance current in the table.

• Repeat the above and complete Table 1.3 (increase $R_s$ by 10 % from balance each time).

1.3.4 Task # 4: Effect of source Voltage value

Now let us investigate how the source voltage $V_s$ affects the sensitivity.

• Set $R_x$ at 1 kΩ.

• Reset the ratio to 1:1 with the ratio arms at $R_1 = R_2 = 100\Omega$ and balance the bridge.

• Set $V_s$ to 12V. Balance the bridge and record the setting in Table 1.4.

• Increase $R_s$ by 10 % and record the out-of-balance current.

• Complete Table 1.4
Figure 1.6: Wheatstone Bridge Connections.
Figure 1.7: Wheatstone Bridge Connections in Tasks # 2 – 4.
Table 1.1: Task #1.

<table>
<thead>
<tr>
<th>$R_1$ (Ω)</th>
<th>$R_2$ (Ω)</th>
<th>$R_x$ (Ω)</th>
<th>$R_s$ (Ω)</th>
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<tbody>
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<tr>
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Table 1.2: Task # 2.

<table>
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<th>$R_s$ at balance (Ω)</th>
<th>Out of Balance Current (µA)</th>
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<td></td>
<td></td>
</tr>
<tr>
<td>1 k</td>
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<tr>
<td>100 k</td>
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</table>

Table 1.3: Task # 3.

<table>
<thead>
<tr>
<th>$R_1$ (Ω)</th>
<th>$R_2$ (Ω)</th>
<th>Ratio ($= \frac{R_s}{R_1}$)</th>
<th>$R_s$ at balance (Ω)</th>
<th>Out of balance current (µA)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>100</td>
<td></td>
<td></td>
<td></td>
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Table 1.4: Task # 4.

<table>
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<th>$R_1$ (Ω)</th>
<th>$R_2$ (Ω)</th>
<th>$V_s$ (V)</th>
<th>Balance (Ω)</th>
<th>Out of Balance Current (µA)</th>
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1.4 DISCUSSION & CONCLUSIONS

It is required to respond to the following question after you complete the experiment in the lab:

1. Task # 1

   (a) If the ratio arms were changed so that $R_1 = 10R_2$, what would be the voltage on the junction of $R_1$ and $R_2$ be, with respect to the source voltage? What ratio of $R_s$ and $R_x$ would give a balance in this case?

   (b) Does the values of $R_s$ calculated agree with those obtained experimentally?

   (c) Mention some sources of errors that could lead to inaccuracy in the results obtained in this task.

2. Task # 2

   (a) Which value gave the greatest out-of-balance current for a 10% change in $R_s$? Which gave the smallest current?

   (b) Which values of $R_1$ and $R_2$ give greatest sensitivity (high or low values)?

   (c) Mention some sources of errors that could lead to inaccuracy in the results obtained in this task.

3. Task # 3

   (a) Which ratio gives the greatest sensitivity (large or low ratios)?

   (b) For the same ratio, which values of $R_1$ and $R_2$ give the greatest sensitivity (high or low values)?

   (c) Mention some sources of errors that could lead to inaccuracy in the results obtained in this task.

4. Task # 4

   (a) Which value of $V_s$ gives the greatest sensitivity (high or low values)?

   (b) The series resistor 220 Ω was removed in task 2,3 & 4, when the circuit still needed protection, why? (Hint: when studying the effect of one variable, fix the others).

   (c) Mention some sources of errors that could lead to inaccuracy in the results obtained in this task.
Chapter 2

Experiment # 2: Operational Amplifier

2.1 OBJECTIVE

When you have completed this experiment you will

- understand the operation of the basic operational amplifier.
- know how to connect up an operational amplifier to act as a voltage amplifier.
- study some of practical issues of operational amplifier.

2.2 BACKGROUND THEORY

During the previous experiment, you have studied the Wheatstone bridge as a conditioning circuit that may be used with sensors that change their resistance with change in the measured variable. During this experiment, you will study the operational amplifier and a few of its application circuits that can be used in signal conditioning. An operational amplifier (op-amp) is a DC-coupled high-gain electronic voltage amplifier with a differential input and, usually, a single-ended output. An op-amp produces an output voltage that is typically hundreds or thousands times larger than the voltage difference between its input terminals.

The circuit symbol for an op-amp is shown by Figure 2.1, where V+: non-inverting input V-: inverting input Vout: output Vs+: positive power supply Vs-: negative power supply Figure 2.2 shows pins out of the op-amp LM741, and Figure 2.3 shows the input output characteristics for an operational amplifier.
Figure 2.1: Symbol of op-amp.

Figure 2.2: Pin out of the op-amp LM741.
Operational amplifier is called this way because can be multi-task devices, which means that they can be implemented in circuits in different configuration to perform different tasks. The following configurations are some of the possible configurations for operational amplifiers.

### 2.2.1 Inverting amplifier

An inverting amplifier, as the one shown in Figure 2.4, uses negative feedback to invert and amplify a voltage. The $R_{in}$, $R_f$ resistor network allows some of the output signal to be returned to the input. Since the output is $180^\circ$ out of phase, this amount is effectively subtracted from the input, thereby reducing the input into the operational amplifier. This reduces the overall gain of the amplifier and is dubbed negative feedback. The relationship relating $V_o$ to $V_{in}$ is given by

$$V_o = -\frac{R_f}{R_{in}} V_{in} \quad (2.1)$$

The input impedance seen by the inverting amplifier input terminals equals $R_{in}$.

### 2.2.2 Non-inverting amplifier

A non-inverting amplifier, as the one shown in Figure 2.5, uses negative feedback to amplify a voltage without inverting it. The relationship relating $V_o$ to $V_{in}$ is given by
2.2.3 Summing amplifier

A summing amplifier, as the one shown in Figure 2.6, uses negative feedback to amplify and invert several input voltages. The relationship relating output voltage to the input voltages is given by

\[ V_o = -R_f \left( \frac{V_1}{R_1} + \frac{V_2}{R_2} + \ldots + \frac{V_n}{R_n} \right) \quad (2.3) \]

The input impedance seen by the non-inverting amplifier input terminals is infinite.
2.2.4 Differential amplifier

A differential amplifier is an amplifier that accepts voltage at both of its inputs and has a negative feedback. Figure 2.7 shows a differential amplifier.

The following equation represents the relationship between the inputs and the output of the differential amplifier shown in Figure 2.7:

\[ V_{\text{out}} = \frac{R_2}{R_1} (V_2 - V_1) \]  

(2.4)

The input impedance seen by the non-inverting amplifier input terminals equals \(2R_1\).

2.3 Op-Amp Input-Output Relationship Derivation

To derive the relationships relating the input and output voltages of the operational amplifier, the following principles must be taken into consideration:

1. The inverting and non-inverting terminals of an operational amplifier can be considered shorted, thus, they have the same voltage. This is called virtually shorted terminals.

2. Because the terminals are virtually shorted, if one of them is grounded, then both of them are grounded and this is called virtually ground.

3. The operational amplifier has the characteristics shown in Figure 2.3, thus it is considered as a linear device and superposition theorem may be applied to it, at least until saturation region is reached.
The following is the derivation of the input output relationship for the non-inverting amplifier shown in Figure 2.4:

- KCL at the inverting terminal node:

\[
\frac{(V_{\text{in}} - V_a)}{R_{\text{in}}} = \frac{(V_a - V_o)}{R_f} \tag{2.5}
\]

- But \( V_a = 0 \) because it is virtually grounded, then:

\[
\frac{(V_{\text{in}} - 0)}{R_{\text{in}}} = \frac{(0 - V_o)}{R_f} \tag{2.6}
\]

- Rearrange to get the form in equation 2.1.

### 2.4 Op-amp Specifications and Practical Issues

Ideal operational amplifier has the following specifications:

1. Infinite input resistance.
2. Zero output resistance.
3. Infinite common mode rejection ratio (CMRR).
4. Zero input current and input voltage offsets.
Real op-amp does not really exist. This will cause some practical issues. Two of these issues are discussed next; the input offset voltage and the input offset current. These offset happens when the output of the op-amp is not zero for a zero input voltage. Because the ideal input resistance of the op-amp is infinity, no current is supposed to flow in it. But due to biasing requirements, a small amount of current flows into the inputs. When large resistors or sources with high output impedances are used in the circuit, these small currents can produce large unmodeled voltage drops. If the input currents are matched, and the impedance looking out of both inputs are matched, then the voltages produced at each input will be equal. Because the operational amplifier operates on the difference between its inputs, these matched voltages will have no effect (unless the operational amplifier has poor CMRR, which is described below). It is more common for the input currents (or the impedances looking out of each input) to be slightly mismatched, and so a small offset voltage can be produced. This offset voltage can create offsets or drifting in the operational amplifier.

The solution to these problems is to null the amplifier to compensate for the offsets. Input offset current compensation can be provided by making the resistance feeding both the input terminals approximately the same. In Figure 2.8, for the inverting amplifier this is done by a resistor on the non-inverting terminal whose value is the same as $R_f$ and $R_{in}$ in parallel which is the effective resistance seen by the inverting terminal.

Compensation for input offset voltage can be done in one of two ways. Many modern op-amp ICs provide terminals to allow input offset compensation. This is shown by Figure 2.8 as a variable resistor connected to two input terminals of the op-amp. The wiper of the variable
resistor is connected to the supply voltage, either $+V_s$ or $-V_s$, according to the specification of the op-amp.

Some op-amps do not provide terminals for input offset compensation in the manner described above. In these cases, a small bias voltage must be placed on the input to provide the required compensation. Figure 2.9 shows one way to do this in the case of a differential amplifier.
2.5 PROCEDURE:

2.5.1 Task # 1:
1. Implement the circuit shown in Figure 2.10 such that the circuit provides a gain of 2.
2. Switch on the power supplies.
3. While $V_{in} = 0$ V, adjust the potentiometer till the output voltage equals 0 V.
4. Complete Table 2.1.

2.5.2 Task # 2:
1. Implement the circuit shown in Figure 2.11 such that the circuit provides a gain of 2.
2. Switch on the power supplies.
3. While $V_{in} = 0$ V, adjust the potentiometer till the output voltage equals 0 V.
4. Complete Table 2.1.

2.5.3 Task # 3:
1. Implement the circuit shown in Figure 2.12 such that the circuit provides a gain of 2.
2. Switch on the power supplies.
3. While $V_{in} = 0$ V, adjust the potentiometer till the output voltage equals 0 V.
4. Complete Table 2.2.
Figure 2.10: Task # 1 circuit.

Figure 2.11: Task # 2 circuit.
Figure 2.12: Task # 3 circuit.
### Table 2.1: Tasks # 1 and 2 Readings

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<th>Output voltage (V) Task # 1</th>
<th>Output voltage (V) Task # 2</th>
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<td>7</td>
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### Table 2.2: Tasks # 3 Readings

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<td>8</td>
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</table>
2.6 DISCUSSION & CONCLUSIONS

It is required to respond to the following question after you complete the experiment in the lab:

1. Plot the output voltage versus input voltage for both tasks 1 and 2 on the same plot. Calculate the slopes of the curves.

2. What is the difference between the curves of task 1 and task 2? Based on this what is the advantage of the summing amplifier. What application it may have because of this advantage.

3. Compare the slope of the curve to the amplifier gain. Calculate the percentage error.

4. Plot the output voltage versus input voltage for tasks 3. Calculate the slope of the curve.

5. For the three tasks, what happens to the output voltage when the input voltage is larger than or equals 6V? What is this phenomena called?

6. Differential amplifier can be used as inverting amplifier but not the other way around. Why? What advantage does the differential configuration holds?

7. Mention some sources of errors that could lead to inaccuracy in the results obtained.
Chapter 3

Experiment # 3: Proximity Sensors

3.1 OBJECTIVE

- To study and understand different mechanisms and principles of some types of digital proximity sensors.
- To observe the response of some types of digital proximity sensors to different materials.

3.2 BACKGROUND THEORY

Sensors dealing with “discrete position”, i.e. sensors which detect whether or not an object is located at a certain position without physically touching them, are known as digital proximity sensors. Sensors of this type provide a “Yes” or “No” statement depending on whether or not the position, to be defined, has been taken up by the object. These sensors, which only signal two statuses, are also known as binary sensors or in rare cases as initiators.

With many production systems, “mechanical” position switches are used to acknowledge movements which have been executed. Additional terms are used such as microswitches, limit switches, or limit valves. Because movements are detected by means of contact sensing, relevant constructive requirements must be fulfilled. Also, these components are subject to wear. In contrast, proximity sensors operate electronically and offer the following advantages:

- Precise and automatic sensing of geometric positions.
- Contactless sensing of objects and processes; no contact between sensor and workpiece is usually required.
• Fast switching characteristics; because the output signals are generated electronically, the sensors are bounce-free and do not create error pulses.

• Wear-resistant function; electronic sensors do not include moving parts which can wear out.

• Unlimited number of switching cycles.

• Suitable versions are also available for use in hazardous conditions (e.g. areas with explosion hazard).

Nowadays, proximity sensors are used in many areas of industry for the reasons mentioned above. They are used for sequence control in technical installations, monitoring, and safeguarding processes. In this context, sensors are used for early, quick and safe detection of faults in the production process. The prevention of damage to man and machine is another important factor to be considered. A reduction in downtime of machinery can also be achieved by means of sensors, because failure is quickly detected and signalled. In this experiment, four types of these sensors will be studied:

• Inductive proximity sensors.

• Capacitive proximity sensors.

• Magnetic proximity sensors.

• Optical proximity sensors.

### 3.2.1 Inductive Proximity Sensors

The sensor incorporates an electromagnetic coil which is used to detect the presence of a conductive metal object. The sensor will ignore the presence of an object if it is not metal, Figure 3.1. This type of sensor consists mainly of four elements: coil, oscillator, trigger circuit, and an output, Figure 3.2. Inductive proximity sensors are designed to generate an electromagnetic field. When a metal object enters this field, surface currents, known as eddy currents, are induced in the metal object. These eddy currents drain energy from the electromagnetic field (causes a load on the sensor) resulting in a loss of energy in the oscillator circuit and, consequently, a reduction in the amplitude of oscillation. The trigger circuit detects this change and generates a signal to switch the output ON or OFF. When the object leaves the electromagnetic field area, the oscillator regenerates and the sensor returns
Proximity Sensors

Figure 3.1: Inductive proximity sensor.

Figure 3.2: Construction of an inductive proximity sensor.

to its normal state. This response is shown in Figure 3.3. The operating distance of an inductive proximity sensor varies for each target and application. The ability of a sensor to detect a target is determined by the material of the metal target, its size, and its shape.

An effect that must be considered when using inductive proximity sensor is the difference between its “operate” and “release” points which is called hysteresis. The amount of target travel required for release after operation must be accounted for when selecting target and sensor locations. Hysteresis is needed to help prevent chattering (turning on and off rapidly) when the sensor and/or target is subjected to shock and vibration. Vibration amplitudes must be smaller than the hysteresis band to avoid chatter. This effect is shown in Figure 3.4.

The advantages of inductive proximity sensors include:

- Not affected by moisture and dusty/dirty environments.
- No moving parts/no mechanical wear.
- Not color dependent.
Figure 3.3: Response of an inductive proximity sensor.

Figure 3.4: Hysteresis effect in an inductive proximity sensor.

- Less surface dependent than other sensing technologies.

The cautions must be taken when dealing with inductive proximity sensors include:

- Only sense the presence of metal targets.
- Operating range is shorter than ranges available in others sensing technologies.
- Maybe affected by strong electromagnetic fields.
3.2.2 Capacitive Proximity Sensors

Capacitive proximity sensor is a noncontact technology suitable for detecting metals, nonmetals such as paper, glass, liquids, and cloth, Figure 3.5. However, it is best suited for nonmetallic targets because of its characteristics and cost relative to inductive proximity sensors. In most applications with metallic targets, inductive sensing is preferred because it is both a reliable and a more affordable technology.

Capacitive proximity sensors consist of four main components: capacitive probe or plate, oscillator, signal level detector, output switching device, Figure 3.6. These sensors are similar in size, shape, and concept to inductive proximity sensors. However, capacitive proximity sensors react to alterations in an electrostatic field. The probe behind the sensor face is a capacitor plate. When power is applied to the sensor, an electrostatic field is generated that reacts to changes in capacitance caused by the presence of a target. When the target is outside the electrostatic field, the oscillator is inactive. As the target approaches, a capacitive coupling develops between the target and the capacitive probe. When the capacitance reaches a specified threshold, the oscillator is activated, triggering the output circuit to switch states between ON or OFF, Figure 3.6.

An important point to be considered while using capacitive proximity sensor is that any material entering the sensor’s electrostatic field can cause an output signal. This includes mist, dirt, dust, or other contaminants on the sensor face. The advantages of capacitive proximity sensors include:

- Detects metal and nonmetal, liquids and solids.
- Can “see through” certain materials (product boxes).
• Solid-state, long life.

• Many mounting configurations.

and the disadvantages of capacitive proximity sensors include:

• Short (1 inch or less) sensing distance varies widely according to material being sensed.

• Very sensitive to environmental factors (humidity in coastal/water climates can affect sensing output).

• Not at all selective for its target, hence, control of what comes close to the sensor is essential.

One application for capacitive proximity sensors is level detection through a barrier. For example, water has a much higher dielectric than plastic. This gives the sensor the ability to “see through” the plastic and detect the level water, Figure 3.7.

### 3.2.3 Magnetic Proximity Sensors

Magnetic proximity sensors are noncontact proximity devices utilize inductance, Hall effect principles, variable reluctance, or magnetoresistive technology. Magnetic proximity sensors
are characterized by the possibility of large switching distances and availability with small dimensions. They detect magnetic objects (usually permanent magnets), which are used to trigger the switching process.

Magnetic proximity sensors are actuated by the presence of a permanent magnet, Figure 3.8. Their operating principle is based on the use of “reed contacts”, which are thin plates hermetically sealed in a glass bulb with inert gas. The presence of a magnetic field forces the thin plates to touch each other causing an electrical contact. The surface of plate has been treated with a special material particularly suitable for low current or high inductive circuits. Magnetic sensors compared to traditional mechanical switches have the following advantages:

- Contacts are well protected against dust, oxidization and corrosion due to the hermetic glass bulb and inert gas; contacts are activated by means of a magnetic field rather than mechanical parts.
- Special surface treatment of contacts assures long contact life.
- Maintenance free.
- Easy operation and small size.

As with other proximity sensors, magnetic proximity sensor suffers from hysteresis phenomenon as shown by Figure 3.8.

### 3.2.4 Optical Proximity Sensors

In its most basic form, a photoelectric sensor can be thought of as a switch where the mechanical actuator or lever arm function is replaced by a beam of light. By replacing the lever arm with a light beam the device can be used in applications requiring sensing distances from less than 2.54 cm (1 in) to one hundred meters or more (several hundred feet). All photoelectric
Proximity Sensors

sensors operate by sensing a change in the amount of light received by a photodetector. The change in light allows the sensor to detect the presence or absence of the object, its size, shape, reflectivity, opacity, translucence, or color. There is a vast number of photoelectric sensors from which to choose. Each offers a unique combination of sensing performance, output characteristics, and mounting options.

A photoelectric sensor consists of five basic components: light source, light detector, lenses, logic circuit, and the output, Figure 3.9. A light source sends light toward the object. A light receiver, pointed toward the same object, detects the presence or absence of direct or reflected light originating from the source. Detection of the light generates an output signal (analog or digital).

Photoelectric sensors can be housed in separate source and receiver packages or as a single unit. An important part of any sensor application involves selecting the best sensing mode for the application. There are three basic types of sensing modes in photoelectric sensors: Transmitted Beam, Retroreflective, and Diffuse sensors.
Transmitted Beam Sensors

In this sensing mode, the light source and receiver are contained in separate housings, Figure 3.10. The two units are positioned opposite each other so the light from the source shines directly on the receiver. The beam between the light source and the receiver must be broken for object detection.

Transmitted beam sensors provide the longest sensing distances and the highest level of operating margin. For this reason, transmitted beam is the best sensing mode for operating in very dusty or dirty industrial environments. The transmitted beam sensor has the following advantages:

- Because of their well-defined effective beam, transmitted beam sensors are usually the most reliable for accurate parts counting.
- Use of transmitted beam sensors eliminates the variable of surface reflectivity or color.
- Because of their ability to sense through heavy dirt, dust, mist, condensation, oil, and film, transmitted beam sensors allow for the most reliable performance before cleaning is required and, therefore, offer a lower maintenance cost.
- Transmitted beam sensors can sometimes be used to “beam through” thin-walled boxes or containers to detect the presence, absence, or level of the product inside.

On the other hand, it has the following disadvantages:

- Very small parts that do not interrupt at least 50% of the effective beam can be difficult to be reliably detected.
Transmitted beam sensing may not be suitable for detection of translucent or transparent objects. The high margin levels allow the sensor to “see through” these objects.

**Retroreflective Sensors**

A retroreflective sensor contains both the emitter and receiver in one housing. The light beam from the emitter is bounced off a reflector (or a special reflective material) and detected by the receiver. The object is detected when it breaks this light beam, Figure 3.11.

A wide selection of reflectors is available. The maximum available sensing distance of a retroreflective sensor depends in part upon both the size and the efficiency of the reflector. For the most reliable sensing, it is recommended that the largest reflector available be used. Retroreflective sensors are easier to install than transmitted beam sensors because only one sensor housing is installed and wired. Retroreflective sensing less desirable in highly contaminated environments. The retroreflective sensor has the following advantages:

- Moderate sensing distances.
- Less expensive than transmitted beam because simpler wiring.
- Easy alignment.

On the other hand, it has the following disadvantages:
Figure 3.12: Diffuse sensor.

- Shorter sensing distance than transmitted beam.
- Less margin than transmitted beam.
- May detect reflections from shiny objects or highly reflective objects.

Diffuse Sensors

Transmitted beam and retroreflective sensing create a beam of light between the emitter and receiver or between the sensor and reflector. Sometimes it is difficult, or even impossible, to obtain access to both sides of an object to install receiver or reflector. In these applications, it is necessary to detect a reflection directly from the object. The surface of object scatters light at all angles; a small portion is reflected toward the receiver. This mode of sensing is called diffuse sensing, Figure 3.12.

Object and background reflectivity can vary widely. Relatively shiny surfaces may reflect most of the light away from the receiver, making detection very difficult. The sensor face must be perpendicular with these types of object surfaces. On the other hand, very dark, matte objects may absorb most of the light and reflect very little for detection. These objects may be hard to detect unless the sensor is positioned very close. The diffuse sensor has the following advantages:
• Applications where the sensor-to-object distance is from a few inches to a few feet and when neither transmitted beam nor retroreflective sensing is practical.

• Applications that require sensitivity to differences in surface reflectivity and monitoring of surface conditions that relate to those differences in reflectivity are important.

On the other hand, it has the following disadvantages:

• Reflectivity: the response of a diffuse sensor is dramatically influenced by the surface reflectivity of the object to be sensed.

• Shiny surfaces: Shiny objects that are at a non-perpendicular angle may be difficult to detect.

• Small part detection: Diffuse sensors have less sensing distance when used to sense objects with small reflective area.

• Most diffuse mode sensors are less tolerant to the contamination around them and lose their margin very rapidly as dirt and moisture accumulate on their lenses.

Hysteresis also appears in optical sensors and is defined as the difference between the distance when a target can be detected as it moves towards the sensor and the distance it has to move away from the sensor to no longer be detected. As the target moves toward the sensor, it is detected at distance X. As it then moves away from the sensor, it is still detected until it gets to distance Y, Figure 3.13. The high hysteresis in most photoelectric sensors is useful for detecting large opaque objects in retroreflective and transmitted beam applications.
References

3.3 PROCEDURE:

1. Connect the circuit shown in Figure 3.14:

2. Approach each of the sensors 1, 2, 3 and 4 with each following materials: plastic, metal, and magnet.

3. For each material and sensor:
   
   (a) Approach the sensor then record the distance in Tables 3.1–3.3 at which the LED/Buzzer turn on.

   (b) Pull away from the sensor and record the distance in Tables 3.1–3.3 at which the LED/Buzzer turn off.

3.4 DISCUSSION & CONCLUSIONS

It is required to respond to the following question after you complete the experiment in the lab:

1. What is the type of each of proximity sensor 1, 2, 3, and 4?
2. Which sensor has the maximum sensing distance? Which one has the minimum sensing distance?

3. Based on your observations in general in this experiment, is it more desirable for sensor to have a large or small sensing distance?

4. Is the switching ON distance the same as the switching OFF distance? If it does not, what is the phenomenon causing this? Explain it in your own words? Which sensor has the largest difference between the ON and OFF distances?

5. For the plastic response to the optical sensor case, draw the output state of the LED versus the distance indicating the hysteresis range. (Use 2 colors in your figure, one for approaching and one for retracting).

6. For the following definition: Hysteresis curve is a curve that shows only the Hysteresis range of a device. Draw the Hysteresis curve for the same case used in the previous question.

7. After studying Tables 3.1–3.3, does the type of the material approaching the sensor affects the switching on distance? Do you see this as an advantage or disadvantage? Explain your answer.

8. Which type of sensor(s) you think most appropriate for each of the following applications (mention the reason behind your selection):
   
   (a) A conveyor belt is to detect the presence of milk cartons.
   (b) The rear (fully retracted) position of a pneumatic cylinder (a magnet is attached to the cylinders piston).
   (c) Detect the presence of shiny objects regardless their materials.
   (d) A milling machine is to detect the presence of iron plates only.
   (e) Detect the presence of wooden boxes in a high humidity environment.

9. Mention some sources of errors that could lead to inaccuracy in the results obtained in Tables 3.1–3.3.
Table 3.1: Response to “PLASTIC” and measurements of distances for sensors used in the experiment.

<table>
<thead>
<tr>
<th>Sensor type</th>
<th>Sensor 1</th>
<th>Sensor 2</th>
<th>Sensor 3</th>
<th>Sensor 4</th>
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<tr>
<td>Switch ON distance</td>
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<td>Switch OFF distance</td>
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Table 3.2: Response to “METAL” and measurements of distances for sensors used in the experiment.

<table>
<thead>
<tr>
<th>Sensor type</th>
<th>Sensor 1</th>
<th>Sensor 2</th>
<th>Sensor 3</th>
<th>Sensor 4</th>
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<tbody>
<tr>
<td>Switch ON distance</td>
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<td>Switch OFF distance</td>
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Table 3.3: Response to “MAGNET” and measurements of distances for sensors used in the experiment.

<table>
<thead>
<tr>
<th>Sensor type</th>
<th>Sensor 1</th>
<th>Sensor 2</th>
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<td>Switch ON distance</td>
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<td>Switch OFF distance</td>
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Chapter 4

Experiment # 4: Variable Length Transducers

4.1 OBJECTIVE

When you have completed this assignment you will

- have confirmed the relationship between length and resistance of a material.
- have observed how the relationship may be used in a variable length transducer.
- have investigated a method of obtaining a direct reading of resistance value.

4.2 BACKGROUND THEORY

We know that the resistance of an object is directly proportional to its length, given by the formula:

\[ R = \frac{\rho \ell}{A} \]  \hspace{1cm} (4.1)

Let us investigate the variation of resistance with length using an apparatus which allows \( \ell \) to be varied whilst keeping the resistivity and the cross-sectional area of the specimen constant. First, examine the Variable Resistor Sub-unit, TK294K, for use with Linear Transducer Test Rig TK294. You will see that it has three connections. Two of these connections are made directly to the resistive element, one at each end of it; the third connection is made to a sliding contact which may travel up and down the resistive element. The position of this sliding
contact may be varied by pushing or pulling the threaded connecting rod. The schematic symbol of the transducer is as shown in Figure 4.1a and the TK294K in Figure 4.1b.

By using one of the fixed connections and the sliding connection a resistive element may be made its effective length varies with the position of the slider, but whose resistivity and cross-section remain constant. This is the situation that we desire. Assemble the TK294K onto the TK294 by aligning the two holes in the assembly with the two pins on the sub-unit, and then dropping the sub-unit into place. The sub-unit is then secured to the assembly by tightening the finger screw. The sub-unit includes a return spring and is operated by pressure applied to the end of the operating rod by the micrometer shaft.

For an operational amplifier circuit with resistive feedback, the equation of operation is given by

\[ V_{\text{out}} = -\frac{R_f V_{\text{in}}}{R_{\text{in}}} \]  

(4.2)

If \( V_{\text{in}} \) and \( R_{\text{in}} \) are kept constant and \( R_f \) is then varied, the output voltage will be directly proportional to \( R_f \).

4.3 PROCEDURE:

4.3.1 Task # 1:

- Connect up the circuit of Figure 4.2. Ensure that the potentiometer is at zero and that the sensor terminals 2 and 3 are used.

- Position the TK249K and subunit such that the sensor is uncompressed.
• Set the variable dc to approximately 10 volts.

• Balance the bridge in the normal manner using the adjustable standard resistor and record your results in Table 3.1.

• Move the slider 5 mm to the left and read its position on the scale.

• Re-balance the bridge and record your result in Table 3.1.

• Repeat the procedure for settings of the slider 5mm apart for the complete range of movement of the transducer.
Table 4.1: Measurements of slider position and corresponding resistance for Task # 1.

<table>
<thead>
<tr>
<th>Slider Position (mm)</th>
<th>Resistance (Ω)</th>
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4.3.2 Task # 2:

- Connect up the circuit of Figure 4.3.
- Return the slider to its furthest right position such that the sensor is uncompressed again.
- Record your readings in Table 3.2.
- Move the slider 5 mm to the left and repeat the readings.
- Repeat this procedure for positions at 5 mm intervals for the full travel of the transducer and record all readings in Table 3.2.
Figure 4.3: A variable length transducer connected to an Op Amp.

Table 4.2: Results of direct resistance reading (Task # 2).

<table>
<thead>
<tr>
<th>Slider position (mm)</th>
<th>Output Voltage (V)</th>
<th>Calculated resistance (kΩ)</th>
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4.4 DISCUSSION & CONCLUSIONS

It is required to respond to the following questions after you complete the experiment in the lab:

• Task # 1

  – Q1: Sketch a schematic diagram for Figure 4.2.
  – Q2: Plot a graph of position against resistance using results you obtained. What type of relationship exists between position and resistor?
  – Q3: Do the results you obtained in Q2 match those of the theory you know? Explain your answer.
  – Q4: If this method was used in practice to measure the position of a moving mechanical part, would the bridge method to determine the resistance be a convenient one?
  – Q5: What is the output of the sensor in this case (voltage, current, resistance)?

• Task # 2

  – Q6: Plot the position against the calculated resistor values from Table 3.2. How does this graph compares to the plot of Q2? (show a sample for the resistor value of calculation).
  – Q7: What advantages does the amplifier method hold over the bridge method? What are the disadvantages?
  – Q8: What is the advantage of positioning the variable length transducer in the feedback of the amplifier (i.e. What is the disadvantage of positioning the variable length transducer in the input of the amplifier)?
  – Q9: What is the output of the sensor in this case (voltage, current, resistance)?
  – Q10: Does the temperature affect the obtained results? (i.e if you performed the experiment in a cold room, will you obtain the same results as if you performed it in a hot room). Explain your answer.
  – Q11: What are the possible sources of error that affect the experiment results? (3 reasons at least)
Chapter 5

Experiment # 5: Thermal Sensors - RTD

5.1 OBJECTIVE

When you have completed this assignment you will

- Study the characteristics of resistance temperature detector (RTD).
- Study the construction, transduction circuit, and application of a PT-100.

5.2 BACKGROUND THEORY

Its surrounding temperature affects the resistance of a conductor. In other words, the variation of the temperature will change the resistance of a conductor. Using this characteristic, we can calculate the resistance from the present temperature value.

RTD (resistance temperature detector) is a wire-wound resistor with a positive temperature coefficient of resistance. The metal used as RTD generally have a low temperature coefficient of resistance, high stability, and a wide temperature detection range. Platinum is the most commonly used material for the RTD. Other materials such as copper and nickel are also suitable for purpose. The resistance vs. temperature curves of platinum, copper and nickel are shown in Figure 5.1:

The resistance vs. temperature characteristic of RTD can be expressed by:

\[ R = R_0(1 + \alpha_1 T + \alpha_2 T^2 + \alpha_3 T^3 + ...) \]  

\[ (5.1) \]
where $R_0$ is resistance at 0°C, $\alpha_1, \alpha_2, \alpha_3...$ are temperature coefficients of resistance, and $T$ is temperature in degrees Celsius. From Equation 5.1, we can see that sometimes RTDs are nonlinear. However, that approximate relationship for the resistance vs. temperature characteristic of RTD between zero and one hundred degrees Celsius can be expressed by:

$$R = R_0(1 + \alpha_1 T)$$

(5.2)

where $\alpha_1$ is 0.00392 °C for platinum. Thus, generally, RTDs are considered linear devices.

The RTD is a wire-wound element. Its internal configurations, two-wire, three-wire and four-wire connections, are shown in Figure 5.2.

The two-wire RTDs advantage is its low cost, however, the characteristics maybe affected by the resistance changes of connecting leads which affects its precision. Therefore, the two-wire RTD is commonly used in application where the resistance changes of leads are less than the resistive changes of the RTD.

The three-wire RTD is suitable for industrial applications where a compromise between precision and cost must be reached. The effects of connecting leads can be reduced by using appropriate wiring arrangements.

Figure 5.3 shows an RTD temperature measurement circuit. If a constant current $I$ is applied to the RTD, the voltage $Vt$ across its two terminals can be measured. Because $I$ is constant, we can use the equation $Rt = Vt/I$ to calculate $Rt$. Finally, calculate the temperature $T$ using the following equations.

$$Vt = I * Rt = I * R_0(1 + \alpha T)$$

(5.3)

$$T = (Vt - I * R_0)/(\alpha * I * R_0)$$

(5.4)

where $I=$ constant current, $R_0 = 100 \, \Omega$, and $\alpha = 0.00392 \, \degree C$.

In most applications, the resistance of connecting leads between the RTD and the transduction circuit will cause some error in measured temperature. Therefore, how to eliminate the effect of connecting wires is an important consideration in designing a transduction circuit.

Resistive sensors usually require circuitry that converts their resistance changes to voltage changes. A resistive bridge (e.g., Wheatstone bridge) is typical for circuits used in many telemetry systems. The two-wire RTD can be connected to the bridge circuit, as shown in Figure 5.4. The RTD resistance $Rt$ and the connection-lead resistance $RL1$ and $RL2$ combine as a bridge arm. This combination will result errors when the bridge is in balance.

Three-wire RTD can also be connected to resistive bridge, as show in Figure 5.5, so that changes in connecting leads are compensated for. All the three connecting leads have the same
length and resistance \((RL_1 = RL_2 = RL_3)\). In Figure 5.5a, lead-resistance changes in the RTD leg of the bridge are compensated for by equal changes in the \(R_3\) leg when the resistance \(R_3\) is approximately equal to the resistance of RTD. In Figure 5.5a, when the bridge balance is reached,

\[
R_1(R_3 + RL_2) = R_2(R_1 + RL_1)
\]

(5.5)

Assume \(R_1 = R_2\), thus

\[
R_3 + RL_2 = R_1 + RL_1
\]

(5.6)

If the connecting leads have the same length and are of the same material, i.e., \(RL_2 = RL_1\), the effect of lead-resistance can be neglected when resistance \(R_3\) is equal to the \(R_t\). In Figure 5.5b, when the bridge balance is reached, then:

\[
R_2(R_t + RL_1) = R_3(R_1 + RL_2)
\]

(5.7)

Assume \(R_2 = R_3\), thus

\[
R_t + RL_1 = R_1 + RL_2
\]

(5.8)

If the connecting leads have the same length and are of the same material, i.e., \(RL_1 = RL_2\), the effect of lead-resistance can be neglected when resistance \(R_1\) is equal to the \(R_t\).

Therefore, we can conclude that for the three-wire RTD, the connecting leads must have the same length and are of the same material. Otherwise, errors caused by the connecting lead will be unavoidable. However, the four-wire RTD, Figure 5.6, has high precision over long distances; but unfortunately, its cost is high.

PT-100 is one form of the RTD. It is made of the platinum wire and has the resistance of 100 \(\Omega\) at 0°C. The construction of PT-100 is shown in Figure 5.7. The platinum wire is wound on a glass or ceramic insulator, which is then installed within a glass or stainless steel protection tube. The gap between the insulator and the protection tube is filled with ceramic or cement. The protection tube is used to protect the sensing element in various measuring environments.

In order to completely understand the interfacing circuits used in this experiment, we review next the concepts of zener diodes and bipolar junction transistors (BJTs). A Zener diode is a type of diode that permits current not only in the forward direction like a normal diode, but also in the reverse direction if the voltage is larger than the breakdown voltage known as “Zener knee voltage” or “Zener voltage”, Figure 5.8. Its symbol is shown in Figure 5.9. Zener diodes are used to maintain a fixed voltage. They are designed to ‘breakdown’ in a reliable and non-destructive way so that they can be used in reverse to maintain a fixed
voltage across their terminals. As shown by Figure 5.8, the zener diode works in three regions. With the aid of Figure 5.10, we will discuss next each of these regions briefly.

1. $V_{BA} > V_\gamma$: the zener diode is forward biased, which means that it acts as normal diode and will have a drop voltage of $V_\gamma$ across it, Figure 5.11.

2. $V_Z < V_{AB} < V_\gamma$: the zener diode is open circuited, Figure 5.12.

3. $|V_{AB}| > |V_Z|$: the zener diode is reveres biased and acts as a voltage regulator “battery” that has a magnitude of $V_Z$, Figure 5.13.

A bipolar junction transistor (BJT) is a three-terminal electronic device constructed of doped semiconductor material and may be used in amplifying or switching applications. The BJTs work in four different modes. Based on those modes, the application of the BJT is determined. Figure 5.14 shows the two types of BJTs. The basic circuit of an “NPN” transistor is shown in Figure 5.15. The working modes of an “NPN” BJT are:

1. Forward Active Mode: $V_{BE} > 0$, $V_{BC} < 0$
   This mode is used in amplification because the emitter and the collector currents are proportional to the base current via the gain $\beta$.

2. Saturation Mode: $V_{BE} > 0$, $V_{BC} > 0$
   The emitter and collector currents are no longer related to the base current. The transistor is saturated which means that $V_{CE}$ is almost zero. So if we are taking the output voltage to equal $V_C$ in a logic circuit, then this will be equivalent to “low” state.

3. Cut-Off Mode: $V_{BE} < 0$, $V_{BC} < 0$
   The emitter, base and collector currents are zero. The transistor is off which means that $V_C$ equals $V_{CC}$. So if we are taking the output voltage to equal $V_C$ in a logic circuit, then this will be equivalent to “High” state.

4. Reverse-Active Mode: $V_{BE} < 0$, $V_{BC} > 0$
   In the reverse active mode, the function of the emitter and the collector is reversed. The bias of the base-emitter junction is reversed and the bias of the base-collector junction is forwarded. But this mode is rarely used.

The four modes are shown in Figure 5.16.
5.3 PROCEDURE:

5.3.1 Task # 1: R vs. T Characteristic of PT-100

- Using Equation 5.2, calculate the resistance \( R_t \) for each 10 °C decrement in temperature starting from 90 °C and record it on Table 5.1.

- Insert the PT-100 into Thermostatic container. Measure and record the resistance for each temperature setting on Table 5.1.

5.3.2 Task # 2: Transduction circuit

- Place module KL-64012 on KL-62001 as shown in Figure 5.17.

- Connect the PT-100 to module KL-64012 and turn on power.

- Using DMM measure the current of PT-100. By adjusting the potentiometer R2 set this current to 2.55 mA.

- Adjust the output voltage at Vf1 to 2.55V DC by adjusting the potentiometer R14.

- Insert the PT-100 into the Thermostatic container.

- Measure and record the output voltage of PT-100 at Vo27 for each temperature setting on Table 5.2.

5.3.3 Task # 3: Fire Alarm

- Place module KL-64012 on KL-62001.

- Repeat Steps 2, 3 from Task # 2.

- Construct the circuit shown in Figure 5.18.

- Review Table 5.2, the output voltage of PT-100 transducer is _______ V at 80 °C.

- Adjust the potentiometer VR so the voltage at VR2 is equal to that of the above step.

- Observe the thermometer and record the temperature at which the buzzer turn on. \( T = \) _______ °C.
Figure 5.1: R vs T curves of Platinum, Copper, and Nickel.

Figure 5.2: Typical internal schematic diagrams of RTDs.

Figure 5.3: RTD measuring circuit.
Figure 5.4: Wheatstone bridge for two-wire RTD.

Figure 5.5: Wheatstone bridge for three-wire RTD.
Figure 5.6: Wheatstone bridge for four-wire RTD.

Figure 5.7: Construction of PT-100.
Figure 5.8: Zener diode characteristics curve.

Figure 5.9: Zener diode circuit symbol.

Figure 5.10: Zener diode in a circuit.
Figure 5.11: Zener diode equivalent circuit in forward bias mode.

Figure 5.12: Zener diode equivalent circuit in cut off mode.

Figure 5.13: Zener diode equivalent circuit in the reverse biased mode.

Figure 5.14: BJT circuit symbol.
Figure 5.15: Basic BJT circuit.

Figure 5.16: Bias modes of operation of a bipolar junction transistor.
Figure 5.17: PT-100 transducer circuit.

Figure 5.18: Fire alarm.
Table 5.1: Calculations of $R_t$ (Task # 1).

<table>
<thead>
<tr>
<th>Temperature ($^\circ$C)</th>
<th>$R_t$ calculated (Ω)</th>
<th>$PT-100$ measured (Ω)</th>
<th>%Error</th>
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</tbody>
</table>

Table 5.2: Measurements of output voltage (Task # 2).

<table>
<thead>
<tr>
<th>Temperature ($^\circ$C)</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>90</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vo27 (V)</td>
<td></td>
<td></td>
<td></td>
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</table>
5.4 DISCUSSION & CONCLUSIONS

It is required to respond to the following questions after you complete the experiment in the lab:

- **Task # 1**
  - **Q1**: Describe the structure of PT-100 used in this experiment.
  - **Q2**: Calculate the percentage error according to the following formula then fill it in Table 5.1.
    \[
    \% Error = \left( \frac{R_{t \text{calculated}} - PT-100 \text{measured}}{R_{t \text{calculated}}} \right) \times 100 \%
    \] (5.9)
  - **Q3**: Plot the theoretical R vs. T curve based on Table 5.1.
  - **Q4**: Plot (on the same above figure) the experimental R vs. T curve based on Table 5.1 and estimate the slope.
  - **Q5**: Describe and compare the curves you obtained in the above point. Mention reasons/sources of differences (at least 3).

- **Task # 2**
  - **Q6**: Plot a voltage versus temperature characteristic curve of the PT-100 transducer using datum from Table 5.2.
  - **Q7**: Observe the curve in Q6, calculate and record the transduction ratio in mV/°C.
  - **Q8**: Analyze the circuit shown in Figure 5.17 and derive the relationship between the output voltage Vo24 and the temperature T. Based on this relationship, what is the transduction ratio in mV/°C.
  - **Q9**: Compare the results of Q7 and Q8 and show percentage error. Is there any difference? Why/why not?
  - **Q10**: Based on your derivation in Q8, state which of the four stages shown in Figure 5.17 corresponds to the following: set point, current source, gain, difference amplifier.
  - **Q11**: What is the use of the zener diode CR2 in stage 1? How it contributes to the purpose of stage 1?
• Task # 3
  – Q12: Describe how the fire alarm circuit shown in Figure 5.18 works.
  – Q13: Does the actual temperature equal to the reference temperature setting?
Chapter 6

Experiment # 6: Photovoltaic and Photoconductive Cells

6.1 OBJECTIVE

When you have completed this experiment, you will

- understand the photovoltaic and photoconductive cells behavior.
- measure the illumination response of photovoltaic and photoconductive cells.

6.2 BACKGROUND THEORY

6.2.1 Photovoltaic Cell

The photovoltaic cell converts light energy into electrical energy without the aid of any external excitation power. The magnitude of its light-sensitive electrical output signal (current or voltage) is directly proportional to the light intensity it is exposed to. It is often referred to as solar cell because they provide a source of electrical power from exposure to sunlight.

Modern photovoltaic cells are introduced to opposite ends of materials such as silicon or germanium, making one end P-type and the other N-type. The P-N junction between them is the potential barrier, as shown in Figure 6.1. The voltage gradient is formed in the depletion region because the energy level in the P-type layer is higher than the energy level in the N-type layer. The upper surface (P-type layer) is a light-transparent layer. The P-N junction acts as a permanent electric field. When the P-type layer is illuminated, the incident photons
cause a flow of electrons and holes. The electric field at the P-N junction directs the flow of electrons toward the N-type layer and the flow of holes toward the P-type layer. The resulting unbalance of charges within the cell will cause an EMF to be developed between two layers.

The EMF can be measured with a high-sensitivity voltmeter. The $V_{op}$ refers to the open-circuit voltage of photovoltaic cell. When a load resistor is connected across the surfaces, electrons and holes carriers flow through the circuit until a state of balance, called equilibrium, is achieved. If the load resistor is replaced by a wire, the current in the circuit is called the short circuit current, $I_{sh}$. If a photovoltaic detector is not illuminated, the V-I characteristic shown in Figure 6.2a is similar to a general-purpose diode. Figure 6.2b shows the V-I characteristic of the photovoltaic cell excited by a weak illumination, Curve 1, and a strong illumination, Curve 2.

Figure 6.3 shows the intensity of incident light versus output signals of a photovoltaic cell. The $V_{op}$ versus the light intensity characteristic is a logarithmic curve, whereas the $I_{sh}$ versus the light intensity is linear.

The output current is commonly used for measuring illumination purposes. In many applications, the I-to-V converters, as the one shown in Figure 6.4, are used for converting the small output current of photovoltaic cells into a more easily measured proportional voltage. Since currents do not enter the terminals of an ideal operational amplifier, the output voltage of a current to voltage converter can be given by the following equation:

$$V_o = -I_{sh} R_f$$  \hspace{1cm} (6.1)

Something worth mentioning here is that the input resistance ($R_{TH}$) seen by the current to
voltage converters is zero.

When a load resistance is connected across the terminals, the value of resistance will change the linearity of \( I_{sh} \) versus illumination curve as shown in Figure 6.5. With a high resistance, the operating point is located in the nonlinear region.
Figure 6.3: Output signals versus incident light.

Figure 6.4: A typical I-to-V converter.

Figure 6.5: Load Lines.
6.2.2 Photoconductive Cell

Electrical conduction in semiconductor materials occurs when free charge carriers are available in the material to move when an electric field is applied. It happens that in certain semiconductors, light energy falling on them is of the correct order of magnitude to release charge carriers which will increase the flow of current produced by an applied voltage. This known as the *photoconductive* effect, and such a device (shown in Figure 6.6) is called a *photresistor, photoconductor, or light dependent resistor LDR*, as incident light will effectively vary its resistance.

We would expect the current, or the number of charge carriers, to be related to the number of photons, or the intensity of the incident light, and we will investigate this. The color of the light will affect the response, due to different energies of the photons, but this will not be investigated in this experiment. A small number of charge carriers are also produced at room temperature by thermal effects, and this will also contribute to the current.
6.3 PROCEDURE:

6.3.1 Task # 1: Photovoltaic cell characteristics

To achieve this task, we will use module KL-64009 on the trainer KL-62001 from K&H company. The circuit of photovoltaic transducer is shown in Figure 6.7. The circuit is used to convert the illumination into output voltages. The photovoltaic set combines four identical cells in series and has a $V_{op}$ about 2V and a $I_{sh}$ about 0.08 A/Ix. The OP AMP U1, $R_6$, and $R_7$ perform the I to V conversion which converts the short-circuit current $I_{sh}$ into an output voltage. The output voltage $V_0$ is given by $I_{sh}(R_6 + R_7)$. The resistance $R_7$ acts as a span adjustment to obtain an output voltage of 1 mV/Ix.

To perform this part and complete Table 6.1, consider the following:

- set illumination by setting lamp voltages as indicated in Table 6.1.
- While the op-amp power is off, measure $V_{op}$ and $I_{sh}$ and record them in Table 6.1.
- Turn the power ON and measure $V_{o24}$. Record the values in Table 6.1.

6.3.2 Task # 2: Photoconductive Cell characteristics

To perform this part, consider the following steps and precautions:

- Mount the lamp holder on the linear transducer test rig.
- Position the optical detector assembly box on the linear transducer test rig in the set of holes nearest the lamp, with the aperture in front of the transducer facing the lamp.
Table 6.1: Readings for photovoltaic characteristics.

<table>
<thead>
<tr>
<th>Relative illumination (%)</th>
<th>$V_{op}(V)$</th>
<th>$I_{sh}(mA)$</th>
<th>$V_{o24}(V)$</th>
</tr>
</thead>
<tbody>
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<td></td>
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</table>

- Connect up the circuit shown in Figure 6.8. Ensure that the photoresistive transducer is set so that its position on the angular scale is 0. Check that the potentiometer control knob on the operational amplifier is set to 0 and switch on the power supply. The lamp should light. Position the lamp holder at the position corresponding to 100% relative illumination.

- Although ambient lighting does not have any great effect, ensure that the transducer is not facing directly into a window or other light source, as excessive lighting could swamp your readings.

- Slowly increase the variable DC control. The meter should indicate a current, when the reading gets about 8 mA STOP.

- Now rotate the optical detector assembly against the scale on the top of the transducer box, so that your milli-ammeter reading is a maximum. You may need to adjust the variable DC output control if you were long way out initially. This ensures that the light is falling perpendicularly on the transducer and we have maximum sensitivity. Do not move this scale during the experiment.

- Leave the equipment like this for at least five minutes, so that the light is continually falling on the transducer. This ensures that the necessary pre-conditioning of the device is carried out.
Table 6.2: Readings of photoconductive cell.

<table>
<thead>
<tr>
<th>Relative Illumination (%)</th>
<th>Scale Setting (mm)</th>
<th>V (V)</th>
<th>I (mA)</th>
<th>Resistance (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>90.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>87.5</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>80</td>
<td>84.0</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>70</td>
<td>80.5</td>
<td></td>
<td></td>
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<tr>
<td>60</td>
<td>75.5</td>
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<tr>
<td>50</td>
<td>69.5</td>
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<tr>
<td>40</td>
<td>61.0</td>
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<tr>
<td>30</td>
<td>48.5</td>
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<tr>
<td>20</td>
<td>40.0</td>
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<td></td>
<td></td>
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<tr>
<td>0</td>
<td>32.0</td>
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</tr>
</tbody>
</table>

- Read the voltage and current and record them in Table 6.2.
- Move the bulb backwards to vary the illumination on the transducer according to Table 6.2 and record the measurements in your own copy.
- If you are doing the experiment in day light, take your readings as quickly as possible because the day light varies. Also keep your hands away from the rig when taking readings because this causes unwanted reflections of the light onto the transducer.
Figure 6.8: Photoconductive cell circuit.
6.4 DISCUSSION & CONCLUSIONS

It is required to respond to the following after you complete the experiment in the lab:

- **Q1:** In addition to the current-to-voltage converter OP AMP, what are the other signal conditioning stages in Figure 6.7? What is the main purpose of them?

- **Q2:** Draw a schematic diagram for the circuit shown in Figure 6.8. Why the voltage is measured across Rx not across the potentiometer?

- **Q3:** For photovoltaic cell, plot $V_{op}$ versus illumination and $I_{sh}$ versus illumination based on Table 6.1. Compare (and comment on) the linearity of the two curves.

- **Q4:** Using $I_{sh}$ versus illumination curve, calculate the transduction ratio of the photovoltaic cell ($\frac{\Delta I_{sh}}{\Delta lx}$).

- **Q5:** Why do we turn power off while measuring $V_{op}$ and $I_{sh}$?

- **Q6:** For the configuration shown in Figure 5.7, it is impossible to measure the voltage across and the current through the photovoltaic cell while the power is ON. Is it possible to calculate either of them as well? If they can be calculated, how would that be done?

- **Q7:** For each illumination in photoconductive cell experiment, calculate the resistance of the transducer by applying ohm’s law (show a sample calculation of your work).

- **Q8:** Plot graph of current flowing in photoconductive cell against relative illumination. What shape is the graph? Does it pass through the origin? Why/Why not?

- **Q9:** Draw the best straight line through the points you plotted in Q8. Calculate the slope of the line.

- **Q10:** When you removed all lighting by turning the transducer to face into the box, did the current through photoconductive cell fall exactly to zero? Why?

- **Q11:** Although the device may be called a photoresistor, and we have calculated its resistance for each illumination, why do you think we have plotted current flowing and not resistance.
Chapter 7

Experiment # 7: Strain Gauges (Load Cells)

7.1 OBJECTIVE

When you have completed this assignment, you will have studied

- the principle, construction, and characteristics of a strain gauge.
- the transduction circuit of a strain gauge.
- the application of a strain gauge.

7.2 BACKGROUND THEORY

7.2.1 Strain Gauges

Strain is defined as the fractional change in length of a body due to an applied force, Figure 7.1. While there are several methods of measuring strain, the most common is with a strain gauge which is a sensor whose electrical resistance varies in proportion to the amount of strain in the element being deformed.

The conductor in Figure 7.1 has a length $L$ and a corresponding resistance $R$. If a compression force is applied to this conductor, then the resistance $R$ will be decreased due to a decrease in length and an increase in area. If a tension force is applied to this conductor, then the resistance $R$ will be increased because of an increase in length and a decrease in area. In other words, when an external force is applied, the conductor changes geometric
shape (assuming that the resistivity of the conductor is constant). The intrinsic resistance of a conductor can be given by

$$R_o = \rho \frac{L_o}{A_o}$$  \hspace{1cm} (7.1)

where \(R_o\) is the resistance in ohms, \(\rho\) is the resistivity in ohms-meter, \(L_o\) is the length in meter, and \(A_o\) is the cross sectional area in square meters.

If a force is applied to the conductor, its length will change by \(\Delta L\) and the new length is \(L_o + \Delta L\). Assuming the volume of the conductor is constant, an increment in the length must cause a decrement in area by \(\Delta A\). Based on this, the characteristic equation of the strain gauge (in theory) is obtained and is given by

$$\Delta R = 2R_o \frac{\Delta L}{L_o}$$ \hspace{1cm} (7.2)

The metallic strain gauge consists of a very fine wire or, more commonly, metallic foil arranged in a grid pattern and is mounted on a backing material. The grid pattern maximizes the amount of metallic wire or foil subject to strain in the parallel direction as shown in Figure 7.2. The strain experienced by the test specimen is transferred directly to the strain gauge, which responds with a linear change in its electrical resistance. Strain gauges are available in a wide choice of shapes and sizes to suit a variety of applications. Commercially, they are available with nominal resistance values from 30 to 3000 Ω, with 120, 350, and 1000 Ω being the most common values.

A fundamental parameter of the strain gauge is its sensitivity to strain, expressed quantitatively as the gauge factor (GF). Gauge factor is defined as the ratio of fractional change in electrical resistance to the fractional change in length (strain):

$$GF = \frac{\Delta R/R}{\Delta L/L} = \frac{\Delta R/R}{\epsilon}$$ \hspace{1cm} (7.3)

The gauge factor for metallic strain gauges is typically around 2.
The strain gauge has been in use for many years and is the fundamental sensing element for many types of sensors, including pressure sensors, load cells, torque sensors, position sensors, etc. Strain gauges are frequently used in mechanical engineering research and development to measure the stresses generated by machinery. Aircraft component testing is one area of application, tiny strain-gauge strips glued to structural members, linkages, and any other critical component of an airframe to measure stress.

The changes in strain gauge are typical small. Thus, sensitive interfacing circuits must be used to detect these changes. The most common interfacing circuit with strain gauges is Wheatstone bridge. The strain gauge is connected into a Wheatstone Bridge circuit with a combination of four active gauges (full bridge), two gauges (half bridge), or, less commonly, a single gauge (quarter bridge). In the half and quarter circuits, the bridge is completed with precision resistors.
Typically, the rheostat arm of the bridge ($R_2$) is set at a value equal to the strain gauge resistance with no force applied. The two ratio arms of the bridge ($R_1$ and $R_3$) are set equal to each other. Thus, with no force applied to the strain gauge, the bridge will be symmetrically balanced and the voltmeter will indicate zero volts, representing zero force on the strain gauge. As the strain gauge is either compressed or tensed, its resistance will decrease or increase, respectively, thus unbalancing the bridge and producing an indication at the voltmeter. This arrangement, with a single element of the bridge changing resistance in response to the measured variable (mechanical force), is known as a quarter-bridge circuit, Figure 7.3.

As the distance between the strain gauge and the three other resistances in the bridge circuit may be substantial, wire resistance has a significant impact on the operation of the circuit. This effect is shown in Figure 7.4. The strain gauge’s resistance ($R_{\text{gauge}}$) is not the only resistance being measured: the wire resistances $R_{\text{wire1}}$ and $R_{\text{wire2}}$, being in series with $R_{\text{gauge}}$, also contribute to the resistance of the lower half of the rheostat arm of the bridge, and consequently contribute to the voltmeter’s indication. This, of course, will be falsely interpreted by the meter as physical strain on the gauge. While this effect cannot be completely eliminated in this configuration, it can be minimized with the addition of a third wire, connecting the right side of the voltmeter directly to the upper wire of the strain gauge, Figure 7.5.

Because the third wire carries practically no current (due to the voltmeter’s extremely high internal resistance), its resistance will not drop any substantial amount of voltage. Notice how the resistance of the top wire ($R_{\text{wire1}}$) has been “bypassed” now that the voltmeter connects directly to the top terminal of the strain gauge, leaving only the lower wire’s resistance ($R_{\text{wire2}}$).
to contribute any stray resistance in series with the gauge. Not a perfect solution, of course, but twice as good as the last circuit. To reduce error of measurement due to temperature, a “dummy” strain gauge in place of $R_2$ is used. So that, both elements of the rheostat arm will change resistance in the same proportion when temperature changes. This will efficiently reduce the effects of temperature change while only the stressed gauge will sense strain. This is shown in Figure 7.6.

Even though there are now two strain gauges in the bridge circuit, only one is responsive to mechanical strain, and thus we would still refer to this arrangement as a quarter-bridge. However, if we were to take the upper strain gauge and position it so that it is exposed to the opposite force as the lower gauge (i.e. when the upper gauge is compressed, the lower gauge will be stretched, and visa-versa), we will have both gauges responding to strain, and
the bridge will be more responsive to applied force. This utilization is known as a half-bridge. Since both strain gauges will either increase or decrease resistance by the same proportion in response to changes in temperature, the effects of temperature change remain canceled and the circuit will suffer minimal temperature-induced measurement error. This circuit is shown in Figure 7.7.

An example of how a pair of strain gauges may be bonded to a test specimen so as to yield this effect is illustrated here in Figure 7.8. With no force applied to the test specimen, both strain gauges have equal resistance and the bridge circuit is balanced. However, when a downward force is applied to the free end of the specimen, it will bend downward, stretching gauge #1 and compressing gauge #2 at the same time as shown in Figure 7.9.
In applications where such complementary pairs of strain gauges can be bonded to the test specimen, it may be advantageous to make all four elements of the bridge “active” for even greater sensitivity. This is called a full-bridge circuit and is shown in Figure 7.10. Both half-bridge and full-bridge configurations grant greater sensitivity over the quarter-bridge circuit, but often it is not possible to bond complementary pairs of strain gauges to the test specimen. Thus, the quarter-bridge circuit is frequently used in strain measurement systems. When possible, the full-bridge configuration is the best to use.

This is true not only because it is more sensitive than the others, but because it is linear while the others are not. Linearity, or proportionality, of these bridge circuits is best when the amount of resistance change due to applied force is very small compared to the nominal resistance of the gauge(s). With a full-bridge, however, the output voltage is directly propor-
Figure 7.11: Differential amplifier.

7.2.2 Differential Amplifier

A differential amplifier is an amplifier that accepts voltage at both of its inputs and has a negative feedback. Figure 7.11 shows a differential amplifier. The following equation represents the relationship between the inputs and the output of the differential amplifier shown in Figure 7.11:

$$V_{out} = \frac{R_2}{R_1}(V_2 - V_1) \quad (7.4)$$

The above equation shows that if a large gain is to be obtained from this kind of amplifier, $R_1$ has to be of a small magnitude which means that its input impedances are rather low compared to that of some other op-amp configurations. The solution to this problem, fortunately, is quite simple. All needed to be done is to “buffer” each input voltage signal through a voltage follower as shown in Figure 7.12.

7.2.3 Instrumentation Amplifier

The differential amplifier configuration shown in Figure 7.12 is a good configuration, but it will be even greater to be able to adjust the gain of the amplifier circuit without having to change more than one resistor value. The solution to this is quite simple and is called an “instrumentation amplifier”, Figure 7.13. The relationship relating the output voltage of the
instrumentation amplifier shown in Figure 7.13 to its input voltages is given by the following equation:

\[ V_{out} = (1 + \frac{2R}{R_{gain}})(\frac{R_2}{R_1})(V_2 - V_1) \]  

(7.5)

Though it may not be obvious by looking at the schematic, the differential gain of the instrumentation amplifier can simply be changed by changing the value of one resistor; \( R_{gain} \). But of course, the overall gain could still be changed by changing the values of some of the other resistors, but this would necessitate balanced resistor value changes for the circuit to remain symmetrical. Note that the lowest gain possible with the above circuit is obtained with \( R_{gain} \) completely open (infinite resistance).

### 7.2.4 Description of Experimental Circuit

Four strain gauges, two on the top side and two on the bottom side of the beam, are used in a Wheatstone bridge with a total gain of \( 2.7 \text{ mV} \pm 10\% /\text{kg} \). The bridge is followed by the instrumentation amplifier shown in Figure 7.14. The recommended excitation voltage to the sensor is \( \pm 5\text{V DC} \). In Figure 7.14, an instrumentation amplifier consists of operational amplifiers U4, U5, and U6, with a total gain of

\[ G = (1 + \frac{2R_{15}}{R_{24} + R_{25}}) \]  

(7.6)

To obtain an output of 1 mV/g, the voltage gain of the instrumentation amplifier must be 250 (4 mV/kg \( \times \) 250 = 1mV/g). Under a null weight condition, the output voltage of the
load cell is not zero, and the output transduction ratio is not exactly at 2.7 mV/kg. The former can be improved with providing an offset voltage to the input of the instrumentation amplifier, and the latter can be improved with adjusting the R24 to increase the voltage gain. The output voltage from the potentiometer may be from +12 to -12 V. By adjusting R22, the transduction output can easily obtain a zero under null weight conditions.
Figure 7.14: Strain gauge transducer circuit.
7.3 PROCEDURE

7.3.1 Task #1

1. Set the strain gauge transducer module KL-64007 block 20 on the trainer kl-62001.

2. Under null weight condition, adjust the potentiometer R22 and measure the output voltage at Vo20 for Vo20 = 0 V.

3. Set the weight of 0.2 kg on the disk and adjust R24 for Vo20 = 0.2 V.

4. Measure and record the output voltage at Vo20 for each weight on Table 7.1 (Important note: before adding more weights, repeat step #2).

<table>
<thead>
<tr>
<th>Weight (g)</th>
<th>0</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>500</th>
<th>600</th>
<th>700</th>
<th>800</th>
<th>900</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vo20 (V)</td>
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<td></td>
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7.3.2 Task #2

1. Repeat the first three steps in Task # 1

2. Measure and record the output voltage at Vo20 for each weight on Table 7.2 (Important note: add weights from minimum to maximum and back to minimum sequentially).

<table>
<thead>
<tr>
<th>Weight (g)</th>
<th>0</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>500</th>
<th>600</th>
<th>700</th>
<th>800</th>
<th>900</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vo20 (V)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weight (g)</td>
<td>800</td>
<td>700</td>
<td>600</td>
<td>500</td>
<td>400</td>
<td>300</td>
<td>200</td>
<td>100</td>
<td>0</td>
<td></td>
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<tr>
<td>Vo20 (V)</td>
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</tbody>
</table>
7.4 DISCUSSION and CONCLUSIONS

1. Derive the transduction ratio of the circuit shown in Figure 7.14. Show the steps of the derivation. (you need to apply the superposition theorem).

2. Plot the voltage vs. weight curve of the system using data of Table 7.1, draw the best fit line.

3. Plot the voltage vs. weight curve of the system using data of Table 7.2, draw the best fit line.

4. Zoom in the plot of the previous point until hysteresis appears. Capture this and add the figure to your report. Can the hysteresis be considered as advantage or disadvantage to the sensor. Explain your answer.

5. From the plot, calculate and record the voltage vs. weight transduction ratio (slope of the best fit line).

\[ \text{V/kg} = \text{mV/g} \]

6. Find the output voltage for a load of 450 g using:

(a) the following interpolation equation and the data in Table 7.1:

\[ V_x - V_{\text{min}} = \frac{V_{\text{max}} - V_{\text{min}}}{W_{\text{max}} - W_{\text{min}}} \times (W_x - W_{\text{min}}) \]  

(7.7)

(b) Using the slope you obtained in Q3.

7. Compare the results obtained in question 4 using the equation:

\[ \%\text{error} = \left| \frac{\text{method 1} - \text{method 2}}{\text{method 1} + \text{method 2}} \right| \times 100 \]  

(7.8)

where method 1 is the result you obtained in Q5.a and method 2 is the result you obtained in Q5.b.

8. Do you think that the position of the load on the cantilever beam affects the measurements? Explain your answer.

9. What arrangement of the gauges in the bridge do you suggest to achieve the output voltage (before the stage of the instrumentation amplifier) you obtained during the experiment? Draw the circuit indicating the strain gauges positions and conditions.
10. A similar sensor to the strain gauges is the variable length transducers you have experimented earlier this course. Mention at least one similarity and one difference between these sensors.

11. What sources of error in this experiment can you think of? Explain your answer.
Chapter 8

Experiment # 8: Design of Optical Transducers Interfacing Circuit

8.1 OBJECTIVE

When you have completed this experiment, you will have

- Studied the principle and construction of optocouplers and relays.
- Designed an interfacing circuit using photoresistors, transistors, zener diodes, and optocouplers.

8.2 BACKGROUND THEORY

This experiment is designed to introduce some new concepts and some applications for the sensors you have learned about through the lab. Also, this experiment will be a chance for you to demonstrate your design abilities as an engineer.

8.2.1 Resistance varying sensors

Resistance varying sensor is a sensor that changes its resistance with the measured variable. During this course, you have learned about four resistance varying sensors: variable length transducer (VLT), resistance temperature detector (RTD), photoresistors, and strain gauges. You have also learned about the interfacing circuits used with theses sensors. During this experiment, you will build an application circuit for one of these four sensors.
8.2.2 Electrical isolation

It is a common practice that all sources in a circuit and measurement instruments should have a common ground. But sometimes, the low control circuit voltage should be isolated from the high main line voltages. For example, when a 5 V DC control circuit aids in driving a 220 V AC motor, it is wrong and hazardous to combine the neutral of the 220 V AC voltage source with the ground of the 5 V DC voltage source. This is due the fact that the control circuit has small DC current that passes in one direction, while the main motor circuit has high current that passes in two directions. Here, the need of an electrical isolation arises. Electrical isolation can be obtained using many methods like mechanical electrical isolation and optical electrical isolation.

Mechanical–Electrical Isolation

This type of isolation can be provided using relays. A relay is an electrically operated switch such as the one shown in Figure 8.1. Current flowing through the coil of the relay creates a magnetic field which attracts a lever and changes the switch contacts. The coil current can be ON or OFF, so relays have two switch positions; normally open position (NO) and the normally closed position (NC).

Relays allow a circuit to switch another circuit where the two circuits are completely
separate from each others. For example, a low voltage battery circuit can use a relay to switch a 230 V AC mains circuit. There is no electrical connection inside the relay between the two circuits; the only links are via magnetic field and mechanical level. The coil of a relay passes a relatively large current as much as 100 mA but can be less than that (30 mA in 12 V relays). Most ICs (chips) cannot provide this current and a transistor is usually used to amplify small IC currents to the larger values required for the relay coils.

**Optical–Electrical Isolation**

This type of isolation can be provided using optical isolators like optocoupler ICs. An optical isolator is a device that is interposed between two systems to prevent one from having undesired effects on the other, while transmitting desired signals between them by optical means. Optical isolators have two parts: optical transmitter and optical receiver. Figure 8.2 shows an optical isolator with a LED as an optical transmitter and a phototransistor as an optical receiver. As long as the LED is OFF, the phototransistor is in the cut-off mode and no current flows through it. Once the LED is ON with enough radiation, the phototransistor will move to the forward active mode or even the saturation mode if the light intensity is enough.

Optical isolators are used in electrical systems to protect humans or machines when high-voltage or high-power equipment is being controlled. In addition, optical isolators are used in electronic circuit design in situations where two circuits have large voltage differences, and yet it is necessary to transfer small electrical signals between them without changing the basic voltage level of either.

![Optical isolator](image-url)
8.3 PROCEDURE:

8.3.1 Part 1:

This part simulates the street lighting system. The objective is to design and build a circuit, using photoresistor, that turns on a LED when a room is completely dark.

1. Measuring the photoresistor resistance.
   Expose the photoresistor to the minimum light intensity possible in the lab and measure the maximum value of the photoresistor resistance.
   \[ R_{\text{max}} = \] 

2. Measuring the LED turn on voltage.
   (a) Connect the circuit shown in Figure 8.3.
   (b) Increase the supply voltage carefully till the LED turn on. Record this voltage.
   \[ V_{\text{LED}} = \]

![Figure 8.3: Measuring $V_{\text{LED}}$.](image)

3. Measuring the Zener diode breakdown voltage.
   (a) Connect the circuit shown in Figure 8.4.
   (b) Increasing Vin and measure Vz, until Vz reaches a fixed value even though Vin is still varying, this fixed value is the zener breakdown voltage.
   \[ V_B = \]

4. Final design step.
For the circuit shown in Figure 8.5, you can assume any value for $R_C$ as long as the collector current is in the range of few hundred mA which is the current that the transistor can handle.

(b) Set $V_{CC}$ to be a little higher than $V_B + V_{LED}$.

(c) Set $R_L$ to a value that will not damage your LED which is in the range of mA.

(d) Calculate the value of $R_1$. You may use the following voltage divider equation (consider $V_\gamma$ to be 0.6 V. You have already found the value of $R_{max}$ in part b):

$$V_\gamma > \frac{R_1}{R_1 + R_{max}} \times V_{CC} \quad (8.1)$$

(e) Build the circuit shown in Figure 8.5 and test it.

### 8.3.2 Part 2:

This part is an application for the optical electrical isolation methods you studied above.

1. Connect the circuit shown in Figure 8.6. (The LED represents a fan and the variable voltage supply represents the output voltage from a thermocouple connected to a differential amplifier).

2. Slowly, increase the supply voltage till LED turns on. Record this voltage.
Figure 8.5: Street lighting system simulator.

Figure 8.6: Electrical Isolation.
8.4 DISCUSSION & CONCLUSIONS

It is required to respond to the following question after you complete the experiment in the lab:

1. Does the circuit shown in Figure 8.7 work as the one shown in Figure 8.5? why/why not?

![Figure 8.7: Question 1.](image)

2. Can you think of a much simpler circuit to substitute the circuit shown in Figure 8.5?

3. If you are to use mechanical isolation in part 2, how would you replace the optocoupler with a relay?
Chapter 9

Experiment # 9: Thermocouples

9.1 OBJECTIVE

When you have completed this experiment, you will have

- Studied the principle, construction, and characteristics of a thermocouple.
- Studied a transduction circuit of a thermocouple.

9.2 BACKGROUND THEORY

In experiment # 4, we studied change in material resistance as a function of temperature. Measurement of resistance change, and hence temperature, requires external power sources. However, there is a large percentage of temperature measurement devices that depends on another electrical behavior of materials. This is characterized by a voltage-generating effect in which an electromotive force (emf) is produced that is proportional to temperature. Such an emf is found to be almost linear with temperature and very repeatable for constant materials. This phenomenon is based on thermoelectric properties of materials.

9.2.1 Thermocouples Principles

A thermocouple is a junction formed from two dissimilar metals. A temperature difference will cause a voltage to be induced as shown in Figure 9.1. Thermocouples are widely used for
temperature measurement because they are inexpensive, rugged and reliable, and they can be used over a wide temperature range. In addition, they can be used over a wide temperature range. If we want to measure the output voltage from a thermocouple, every connection of different materials made in the thermocouple loop for measuring devices, extensions leads, and so on will contribute to the total an emf, depending on the difference in materials and various junction temperatures. The problem of the extension leads is shown in Figure 9.2.

Figure 9.3 shows an equivalent circuit to the circuit shown in Figure 9.2. From this figure, you can notice the measurement junction J1, which should be the only junction responsible for the emf measured by the voltmeter. But you must also notice two other junctions; J2 and J3. These junctions are created between both of metals A and B and the copper extension wires connected to the measurement device. These additional junctions mean that there is an extra two sources for emf generation. To produce an output that is definite with respect to the temperature to be measured, the extra two junctions must be forced to be at a known common temperature. In which case the junction is known as reference junction.

For the arrangement in Figure 9.3, the generated emf depends only on the temperature
difference (T1-TR) and the type of metals A and B. The voltage produced has a magnitude dependent on the absolute temperature difference between the measurement junction and reference junction. Polarity depends on which junction is a higher temperature and which metal (A or B) is more positive than the other. In Figure 9.4, J2 and J3 are placed in an ice bath, which means that the reference junctions are at 0°C.

### 9.2.2 Thermocouple Types

Thermocouples come in many standard types which are manufactured from certain alloys and given designation as J, T, K, E, S and R. These types differ in many aspects such as range, linearity, time response, and sensitivity. Based on these aspects, TCs are chosen for
a specific application. Figure 9.6 shows the curves of voltage versus temperature for three types of thermocouples for a reference temperature of 0°C.

It can be noted from Figure 9.6 that type J- and K-types TCs have high slope, i.e. high sensitivity, making measurements easier for a certain change in temperature. On the other hand, S-type TC has less slope, and consequently sensitivity, but it has a larger measurement range of temperature. Another important feature is that these curves are not exactly linear. To take advantage of the inherent accuracy possible with these sensors, comprehensive TC tables are used such as Table 9.1 that shows the output voltage for certain values of measured temperature at a reference temperature of 0°C.

9.2.3 Thermocouple Tables

Temperature Interpolation

The TC tables simply give the voltage that results for particular type of TC when the reference junctions are at a particular reference temperature, and the measurement junction is at a temperature of interest. Referring to the Table 9.1, for example, a K-type TC at 210°C with a 0°C reference results in a TC output voltage of 8.54 mV. In most cases, the measure voltage does not fail exactly on a table value. When this happens, it is necessary to interpolate between table values that bracket the desired value. In general, the value of temperature can be found using the following interpolation equation:

$$T_M = T_L + \left( \frac{T_H - T_L}{V_H - V_L} \right)(V_M - V_L)$$  \hspace{1cm} (9.1)
where $T_M$ is the measured temperature ($^\circ$C), $V_M$ is the measured voltage (V), $V_H$ is a voltage just higher than $V_M$ and is available in Table 9.1, $V_L$ is a voltage just lower than $V_M$ and is available in Table 9.1, $T_H$ is the corresponding temperature to $V_H$ ($^\circ$C), $T_L$ is the corresponding temperature to $V_L$ ($^\circ$C).
Table 9.1: K-type TC table at $T_{ref}=0^\circ C$ (voltage is in mV).

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Change of Table Reference

As mentioned before, Table 9.1 is obtained at 0°C reference temperature. So if the temperature is to be measure at a different temperature like 25°C, a correction factor has to be subtracted. For example, if the $V(210^\circ C)$ is to be measured at reference of 25°C then:

$V(210^\circ C)$ at 0°C reference = 8.54 mV.
$V(25^\circ C)$ at 0°C reference = 1 mV.

then, $V(210^\circ C)$ at 25°C reference = 8.54 - 1 = 7.54 mV.

9.3 PROCEDURE:

9.3.1 Thermocouple Manufacturing

You will manufacture a thermocouple simply by welding the dark blue and red wires from one side. The dark blue and red wires are the BS color code for a K-type thermocouple.

9.3.2 Thermocouple Measurements

1. Weld the copper extension leads to the thermocouple wires (make sure that the copper wires are of the same length).

2. Connect the circuit shown in Figure 9.7.

3. Set R1 to 1 1 kΩ and R2 to 1000 kΩ.

4. Null the operational amplifier using the potentiometer R3.

5. Connect the DMM to measure the output voltage.

6. Measure the room temperature and record it.

7. Insert the thermocouple into the Thermostatic container.

8. Measure and record the output voltage for each temperature setting on Table 9.2.

9. Repeat the steps from 3 to 7 for R1=1 kΩ and R2=2000 kΩ. and fill in Table 9.3.
9.4 DISCUSSION & CONCLUSIONS

It is required to respond to the following question after you complete the experiment in the lab:

1. Mention another type of TCs and metals used in building it. Which metal is positive with respect to the other metal?

2. The junction between TC wires and the extension leads wires will be at the room temperature. Will this cause a problem that cannot be fixed? If you can fix the problem, how will you accomplish that?

3. Calculate the gain for both case 1 and case 2.

4. Calculate the theoretical output voltage of the conditioning circuit expected for each temperature value listed in Table 9.2 and 9.3.
5. Plot the output voltage versus temperature theoretically and experimentally on the same graph for case 1.

6. Repeat the above for case 2.

7. Which of the two cases compares better to the K-type thermocouple tables? (Calculate the percentage error). Show a sample for calculations.

8. Is the graph a straight line within the accuracy of your observation and plotting?

9. Linearize the curves of both cases 1 and 2 and calculate their slope in mV/°C?

10. State three sources for the errors in the experiment.

11. What additions to the circuit in Figure 9.7 do you suggest to improve its results?
### Table 9.2: Case 1: Reference junction temperature: ____________

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<th>Vout (V) theoretically</th>
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### Table 9.3: Case 2: Reference junction temperature: ____________

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